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Surface Runoff and Tile Drainage Transport of Phosphorus in the Midwestern United States

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Abstract

The midwestern United States offers some of the most productive agricultural soils in the world. Given the cool humid climate, much of the region would not be able to support agriculture without subsurface (tile) drainage because high water tables may damage crops and prevent machinery usage in fields at critical times. Although drainage is designed to remove excess soil water as quickly as possible, it can also rapidly transport agrochemicals, including phosphorus (P). This paper illustrates the potential importance of tile drainage for P transport throughout the midwestern United States. Surface runoff and tile drainage from fields in the St. Joseph River Watershed in northeastern Indiana have been monitored since 2008. Although the traditional concept of tile drainage has been that it slowly removes soil matrix flow, peak tile discharge occurred at the same time as peak surface runoff, which demonstrates a strong surface connection through macropore flow. On our research fields, 49% of soluble P and 48% of total P losses occurred via tile discharge. Edge-of-field soluble P and total P areal loads often exceeded watershed-scale areal loadings from the Maumee River, the primary source of nutrients to the western basin of Lake Erie, where algal blooms have been a pervasive problem for the last 10 yr. As farmers, researchers, and policymakers search for treatments to reduce P loading to surface waters, the present work demonstrates that treating only surface runoff may not be sufficient to reach the goal of 41% reduction in P loading for the Lake Erie Basin.

The Great Lakes contain 21% of the world's surface fresh water and 84% of the fresh water supply in North America (USEPA, 2013). Although Lake Erie is the smallest of the Great Lakes, its tourism generates more than $7.4 billion annually, and its ports spawn approximately $1 billion in revenue (USDA-NRCS, 2005). Additionally, it is estimated that sport fishing on Lake Erie brings in hundreds of millions of dollars annually to communities surrounding the lake. At one point, there were more than 1200 charter boats on Lake Erie. Today that number is estimated to be less than 800 (Frankenberger et al., 2012).

As the southernmost, warmest, and shallowest of the Great Lakes, Lake Erie is the most susceptible to the persistence of harmful and nuisance algal blooms (HNABs), including *Lyngbya wollei* and *Microcystis* (Bridgeman et al., 2012; Wynne et al., 2013; Bridgeman et al., 2013). In September 2013, the city of Toledo, Ohio, detected the hepatotoxin microcystin in water intended for drinking from Lake Erie (T. Murphy, personal communication), but the concentration was below the 1.0 μg L^{-1} level that may pose a health risk (World Health Organization, 2003). However, Carroll Township, a small community to the east of Toledo with a water treatment plant that serves roughly 2000 residents, had a detection of microcystin at 3.56 μg L^{-1}, which resulted in a "Do Not Consume" order (Henry, 2013). The drinking water treatment facility was shut off for 2 wk, and water had to be transported into the community.

Phosphorus (P), which exists in aquatic environments as phosphate, organic P compounds, or sediment-bound P, is one of the primary contributors to the dominance of HNABs in lakes (Downing et al., 2001; Davis et al., 2009), and multiple studies of Lake Erie have confirmed that P is primarily limiting both algae and cyanobacteria (Chaffin et al., 2011). Indeed, cultural eutrophication is not a new phenomenon for Lake Erie; excess algal growth and hypoxia were common in the 1960s. Through a series of efforts starting with the Great Lakes Water

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Abbreviations: HNAB, harmful and nuisance algal bloom; NSERL, National Soil Erosion Research Laboratory; SP, soluble phosphorus; TP, total phosphorus.

Quality Agreement of 1972, eutrophication was reduced in the mid-1990s. However, eutrophication issues have since returned (Scavia et al., 2014). Data from the National Center for Water Quality Research's long-term monitoring program demonstrate that soluble P (SP) concentrations and loads have been increasing drastically since the mid-1990s in rivers that feed Lake Erie from agricultural regions; however, there has been negligible change for total P (TP) concentrations and loads in those rivers (Joosse and Baker, 2011). In contrast, no changes have been detected in the urban Cuyahoga River. Furthermore, of the 10,875 Mg of TP that entered Lake Erie on an annual average basis between 1994 and 2008 (Dolan and Chapra, 2012), only 4% came from the upper Great Lakes, and 6% came from atmospheric deposition (Fig. 1). An estimated 70% of the TP loading to Lake Erie is from tributaries, and a majority of the tributary loading has been attributed to nonpoint sources (Dolan and McGunagle, 2005). SPARROW modeling has estimated that 49% of the P in the Maumee River comes from agricultural sources (Robertson and Saad, 2011), although Richards et al. (2013) have argued that this is an underestimate. Using these figures, approximately 3700 Mg P entering the lake annually is related to agricultural activities.

Tile drainage is essential to efficient agricultural production in the cool humid regions of the upper midwestern United States. In the spring, when corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] crops need to be planted, precipitation often exceeds potential evapotranspiration (King et al., 2014a). Without subsurface tile drainage, many fields would remain too wet for farm machinery. This situation is also common in the fall when these crops are being harvested. Tile drainage in these fields also removes excess soil water that can damage crops when anoxic conditions develop (Fausey et al., 1987). It has been estimated that 25% of cropland in the United States and Canada could not be in production without subsurface tile drainage (Skaggs et al., 1994), and 37% of midwestern croplands benefitted from subsurface drainage (Zucker and Brown, 1998). More recently, based on the fact that headwater streams and agricultural ditches account for 80% of the surface drainage network in the Great Lakes Region of the upper midwest, Blann et al. (2009) suggested that the extent of tile drainage is significantly greater than those previous estimates. Furthermore, the most extensive tile drainage in the United States is found in the same regions as the most productive soils and croplands (Smith and Pappas, 2007). Tile drainage has allowed them to be productive (Nizeyimana et al., 2001; Smith and Pappas, 2007).

For a comprehensive review of the impacts of tile drainage on hydrology and stream transport, see King et al. (2014c). Tile drainage can lead to increased discharge of water to receiving waters by 10 to 25% (Serrano and Irwin, 1985; Magner et al., 2004; Tomer et al., 2005). Other studies have indicated that 42 to 86% of streamflow is attributable to tile drains (Macrae et al., 2007; Xue et al., 1998). Leaching of P to tile is enhanced when soils have low P sorption capacity, are prone to developing preferential flow paths, or maintain reducing conditions (Gburek et al., 2005). Schoumans and Breeuwsma (1997) found that soils with high P saturation contributed only 40% of TP load, and another 40% of the TP load came from areas where the soils had only moderate P saturation but had some degree of hydrological connectivity with the drainage network. Preferential flowpaths allow P to bypass the soil matrix, where physiochemical processes

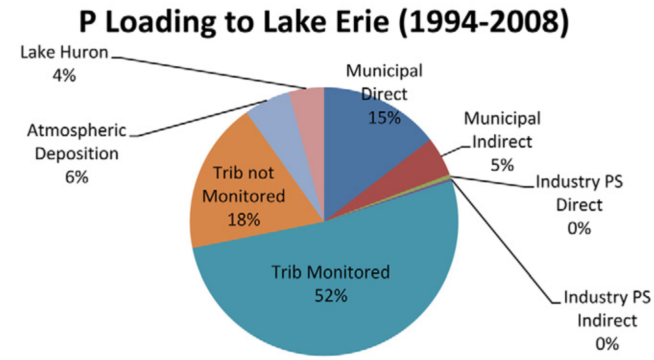

Fig. 1. Sources of phosphorus loading to Lake Erie during the period 1994–2008 (adapted from Dolan and Chapra [2012]). PS, point source.

can decrease the likelihood of losses from fields. Because there is generally no treatment of tile water before being conveyed to the stream network, installation of tile greatly increases the connectivity of fields. This effectively decreases the transport length for any point within a field from the distance surface runoff water would traditionally flow to reach the nearest water body through dendritic flowpaths or as groundwater flow to the depth of the tile (generally 0.9 m). For closed depressional areas (Smith et al., 2008; Smith and Livingston, 2013), the runoff water in an undrained landscape would likely be lost through evapotranspiration; however, in the drained landscape, this runoff water is generally removed from fields through surface tile risers (Smith and Livingston, 2013). Thus, supplemental surface drainage of the landscape results in greater connectivity of surface runoff water as well as the subsurface drainage water.

The primary focus of tile water quality research has been on NO_3–N because it is a highly mobile nutrient and is known to move rapidly to tile drains. Concentrations of NO_3–N can often exceed 10 mg L^{-1} in drainage water (Baker et al., 1975; Logan et al., 1980; Kladivko et al., 1991) and are often greater in drainage water than in surface runoff water. In contrast, the prevailing view of P has been that it is largely immobile and that its loss is driven more by surface runoff processes than by tile drainage processes (Brady and Weil, 1999). Compared with NO_3–N, the relatively low levels of P lost through tile drainage have historically been dismissed (Baker et al., 1975; Kladivko et al., 1991). However, these losses may be significant with respect to enrichment of surface water bodies (Ryden et al., 1973). Other researchers in New Zealand observed the importance of tile drains as a source of P transport (Sharpley and Seyers, 1979a, 1979b). Sims et al. (1998) concluded that P is transported through tile drainage and represents a significant portion of the total amount of P transported. Therefore, the objective of this paper is to present the results of research on surface runoff and tile drainage from watersheds in the Maumee Basin and to determine the importance of tile drainage for P transport throughout the midwestern United States, and particularly for Lake Erie, where P loading is a very important issue.

Materials and Methods

The USDA–ARS National Soil Erosion Research Laboratory (NSERL) has been monitoring water quality and quantity along with meteorology in the St. Joseph River watershed in northeast Indiana since 2002. For this study, surface runoff and tile drainage discharge data from four fields were used. Two fields (Fields 1 [2.2 ha] and 2 [2.7 ha]; Fig. 2) represent typical dendritic flowpaths. Two other fields (Fields 3 [4.0 ha] and 4 [3.5 ha]; Fig. 2) represent closed depressions, commonly referred to as potholes (Smith et al., 2008; Smith and Livingston, 2013). Surface runoff monitoring began in 2004 for Fields 1 and 2 and in 2006 for Fields 3 and 4. Subsurface tile drainage monitoring was added to Fields 1, 2, and 3 in 2008 and to Field 4 in 2009.

Drop box weirs were used in Fields 1 and 2 to monitor surface runoff discharge and to collect runoff water samples for chemical analyses. Surface runoff from Fields 3 and 4 was considered to be the ponded water contained in the closed depression. Typically, closed depressions require surface drainage to ensure ponded water is removed quickly enough to prevent damage to crops. To accomplish this, the industry standard practice is a tile riser, which is a pipe extending above the soil surface, with openings from 1 to 2 cm in diameter, that typically conveys water directly to the subsurface drainage network. At Fields 3 and 4, the runoff water could be drained through a tile riser or a blind inlet (a conservation practice to filter water before entering the tile network). Gate valves allowed drainage to occur through either practice. Generally speaking, the two fields were not drained with the same practice, and the drainage practice was periodically altered within each field. Surface runoff water from Fields 3 and 4 was conveyed to an outlet tile through 10-cm-diameter enclosed PVC pipe as opposed to the perforated subsurface tile pipe. For further details on the sampling protocol and equipment, see Smith and Livingston (2013).

The subsurface drainage at the four field sites was monitored using standard corrugated, perforated tile lines that existed in the fields before the start of this study. In all of the fields, the monitored tile lines did not have any supplemental surface connections (i.e., no tile riser or blind inlet connections).

Water quality samples in surface runoff and in the subsurface tile from storm events were collected using ISCO 6712 autosamplers. The automated water samplers were modified with refrigeration units to cool samples to 4°C on collection. At Fields 1 and 2, surface runoff discharge was calculated by recording the water level flowing through the weirs using a pressure transducer and a calibration curve developed when the drop box weirs were installed. For Fields 3 and 4, surface runoff was monitored using

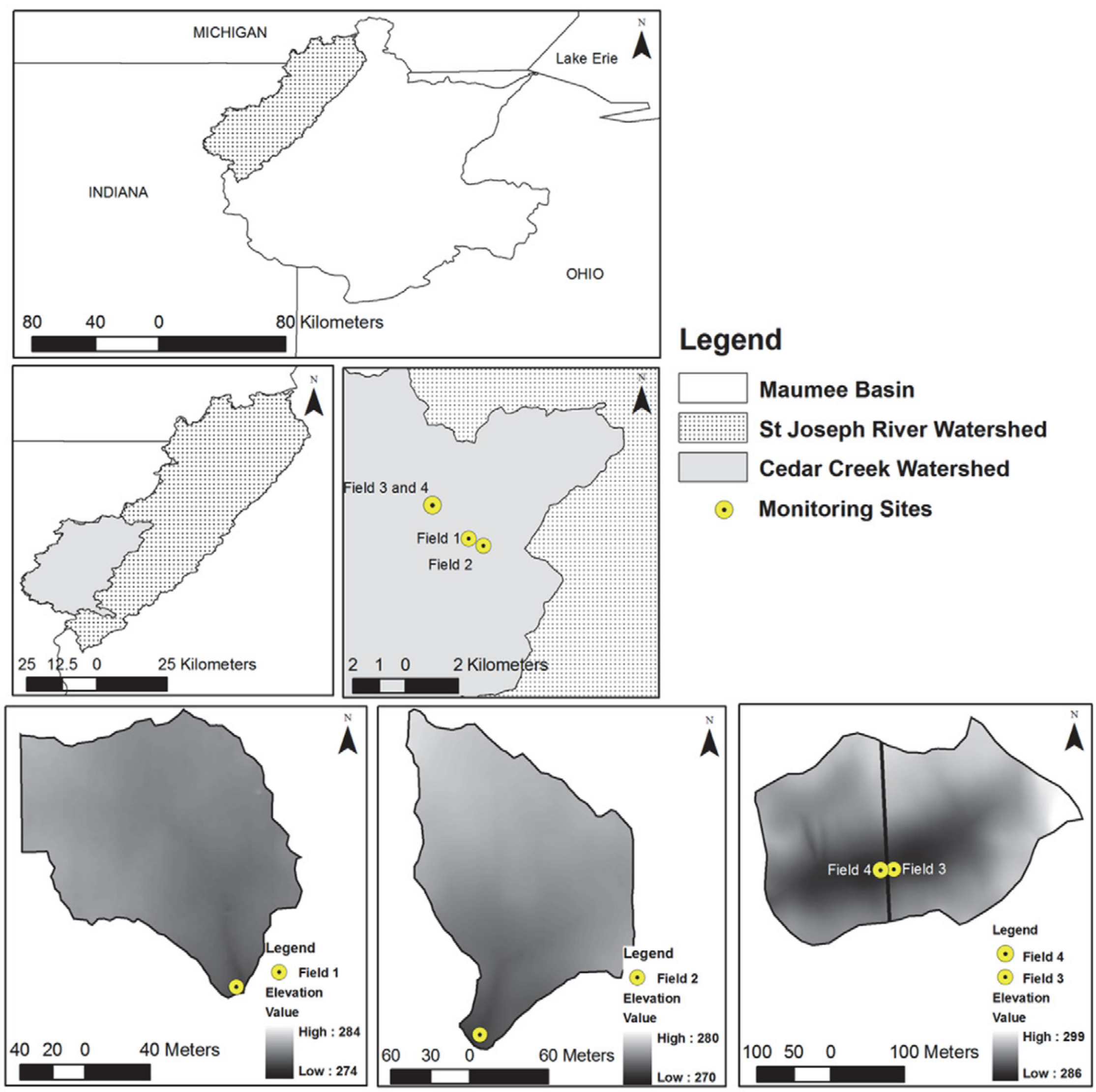

Fig. 2. Map of field monitoring locations in the St. Joseph River watershed, Indiana, which is a tributary to the Maumee River in the western Lake Erie basin.

area velocity sensors placed in the pipe. Similarly, subsurface tile discharge for all fields was measured using area velocity sensors in the tile line.

Water quality samples were removed from the ISCO samplers within 48 h of collection. These samples were transported to an initial processing laboratory located nearby. Aliquots for total nutrient analysis were poured into 60-mL bottles, and 20 mL of the samples was filtered (0.45 μm) and acidified (pH <2) in preparation for the analysis of soluble nutrients. These aliquots were then frozen and transported to the NSERL for analysis.

All nutrient analyses were conducted colorimetrically with a Konelab Aqua 20 (EST Analytical). Soluble P was analyzed on the filtered acidified samples using USEPA Method 365.2 (USEPA, 1983). Total P was analyzed using USEPA Method 365.4 for TP (USEPA, 1983) after mercuric sulfate digestion of the unfiltered samples.

Results and Discussion

Hydrology of Surface Runoff and Tile Discharge

Surface runoff from dendritic flowpaths (Fields 1 and 2) is similar to that of surface runoff from closed depressions (Fields 3 and 4). The processes that result in the production of runoff in either case are infiltration excess or saturation excess overland flow. The primary difference between these two is that the dendritic flowpaths allow water to naturally leave the field from which they are generated, whereas the closed depression runoff collects at the lowest point in the landscape where it ponds. Mechanical intervention (e.g., a surface drainage connection) is required to remove this water from closed depressions despite the processes that induced the surface runoff. Therefore, we consider both sources of water to be surface runoff water and considered each field to be monitored for surface runoff water separately from tile drainage water.

Tile drainage is a function of physical characteristics (e.g., soil conductivity, depth of tile, and lateral spacing) and climatic variables (e.g., precipitation amount, duration, and intensity as well as antecedent moisture conditions) (Heppell et al., 2002; King et al., 2014a, 2014c). Tile drainage generally increases the water storage capacity of the soil profile (Skaggs and Broadhead, 1982), resulting in less surface runoff and reduced peak flows (Skaggs et al., 1994). However, in some instances tile drainage has increased peak discharges (Wiskow and van der Ploeg, 2003). Thus, total water yield, timing, and shape of the hydrograph are affected by tile drainage (Blann et al., 2009).

Traditionally, tile discharge is assumed to be a function of soil matrix release of water to tile; thus, surface runoff occurs before discharge in tile. However, in our monitored tile in the St. Joseph River watershed in northeastern Indiana, peak tile discharge occurred often concurrent with or even shortly before peak discharge in surface runoff (Fig. 3). When 1.85 cm of precipitation fell on Field 2 in May 2011, the resulting discharge was 0.08 cm surface runoff and 0.41 cm from the tile (Fig. 3A). Peak discharge occurred in tile (7.07 L s^{-1}) and surface runoff

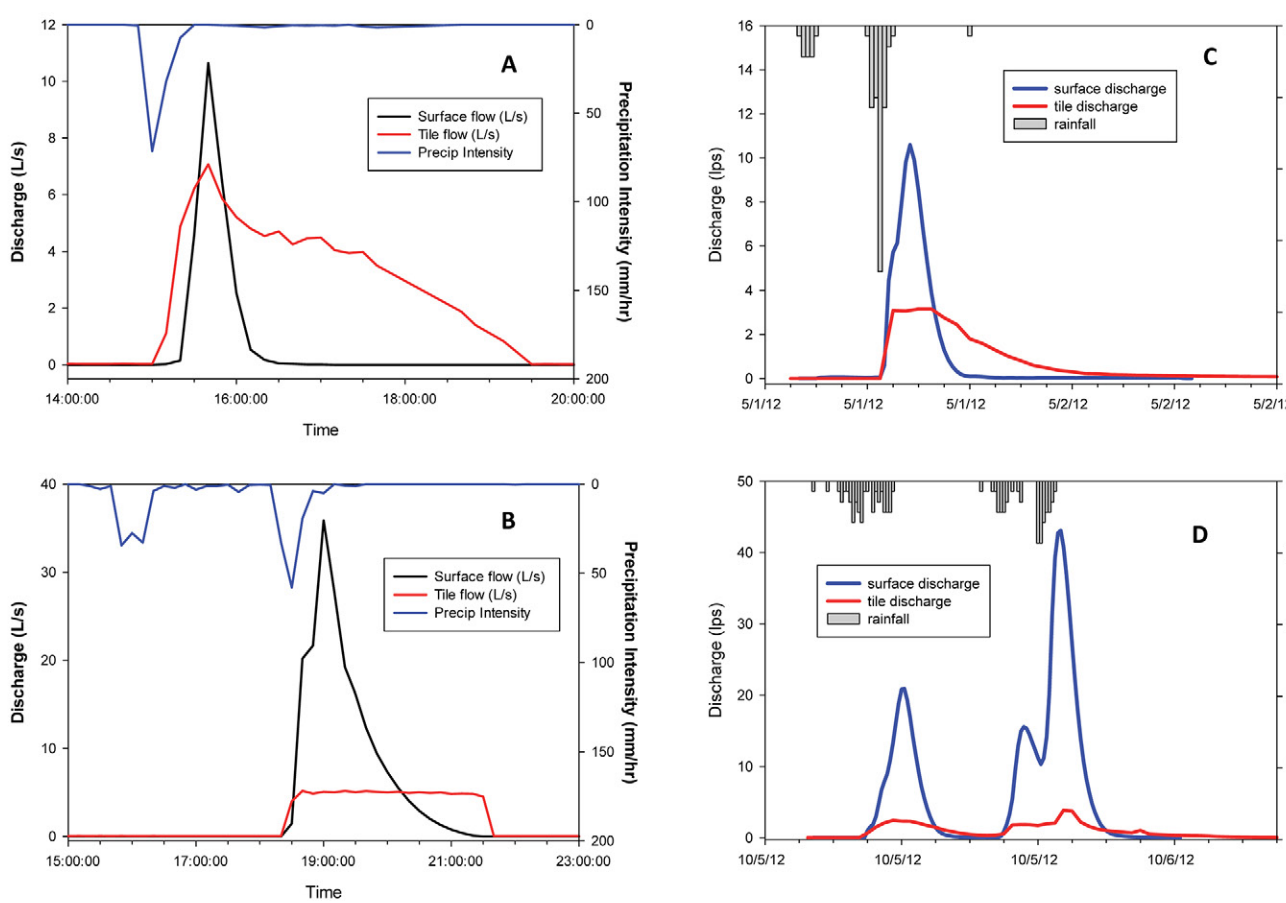

Fig. 3. Precipitation, surface runoff discharge, and tile discharge from monitored fields in the midwestern United States. (A) Storm occurring 14 May 2011 on Field 2 in the St. Joseph River Watershed, Indiana. (B) Storm occurring 7 Apr. 2010 on Field 1 in the St. Joseph River Watershed, Indiana. (C) Storm occurring 1 May 2012 on a field in Ohio. (D) Storm occurring 5 Oct. 2012 on a field in Ohio.

(10.7 L s^{-1}) simultaneously. In April 2010, with 4.34 cm of precipitation at Field 1, 0.58 cm was discharged through the tile, and 1.77 cm was surface runoff (Fig. 3B). In this event, peak discharge in tile (5.2 L s^{-1}) was about 20 min before peak surface runoff discharge (35.9 L s^{-1}). Similar findings have been reported for edge-of-field sites in Ohio (Fig. 3C and 3D). Contrary to expectation, surface water seems to rapidly percolate through the soil to the tile; thus, peak discharge in tile occurs at approximately the same time as surface runoff.

Although many studies have focused on nutrient transport from tile, few studies have reported on the timing of tile discharge or peak tile discharge relative to peak surface runoff. Tomer et al. (2010) reported discharge from a single storm as monitored at the outlet of a tile to a stream and from a field runoff flume. Based on this report, peak surface runoff discharge and tile discharge appeared to occur simultaneously. A study conducted in Illinois also showed that tile discharge peaked early during storm events, although the hydrology of surface runoff was not reported (Gentry et al., 2000). Similarly, Schilling and Helmers (2008) observed that peak tile discharge into a stream occurred very early in the event. Simultaneous peak discharge in tile and surface runoff indicates connectivity of surface water to the tile, most likely through macropore flow. Surface soil test P levels have been shown to be a good indicator of P in drainage water, particularly where macropore flow is prevalent (McDowell and Sharpley, 2001).

Tile Phosphorus Loading Relative to Total Loading

Overall, 49% of the SP loading and 48% of the TP loading occurred through subsurface tile at the four monitored fields (Fig. 4). When looking at individual fields, median relative tile discharge over the 2008 to 2013 period ranged from 42% in Field 2 to 78% for Field 3. The range in median relative SP loading was 18 and 73% from Fields 1 and 3, respectively. Over the 6-yr period, median relative TP loading from the four fields ranged from 27 to 82%. Whereas Field 3 had the greatest relative tile contributions for NO_3–N loading, more than 70% of NO_3–N loading from Fields 1 and 2 was from the tile (data not shown). These observations confirm that at these sites, NO_3–N transport was dominated by subsurface processes. Although P loss is often assumed to be dominated by surface runoff processes (e.g., Brady and Weil, 1999), our P loading results indicate substantial P loss via subsurface transport.

The relative SP and TP loading from tile in the four fields was generally lower than the relative tile discharge, and these values were similar to edge-of-field losses measured in Canada (Enright and Madramootoo, 2003). However, our results were consistently higher than those reported by Zhao et al. (2001), who found that 0.2 to 24% of SP and 0.4 to 21% of TP occurred through tile from a single storm in a closed depressional landscape, similar to Fields 3 and 4. In a headwater watershed in Ohio, tile drainage accounted for 47% of the SP and 43% of the TP exiting the watershed (King et al., 2014b).

Edge-of-Field Surface and Tile Loading Compared with Maumee Loading

Soluble P and TP areal loading from fields, including surface runoff and tile discharge pathways, often exceeded the loading to Lake Erie from the mouth of the Maumee River (Fig. 5).

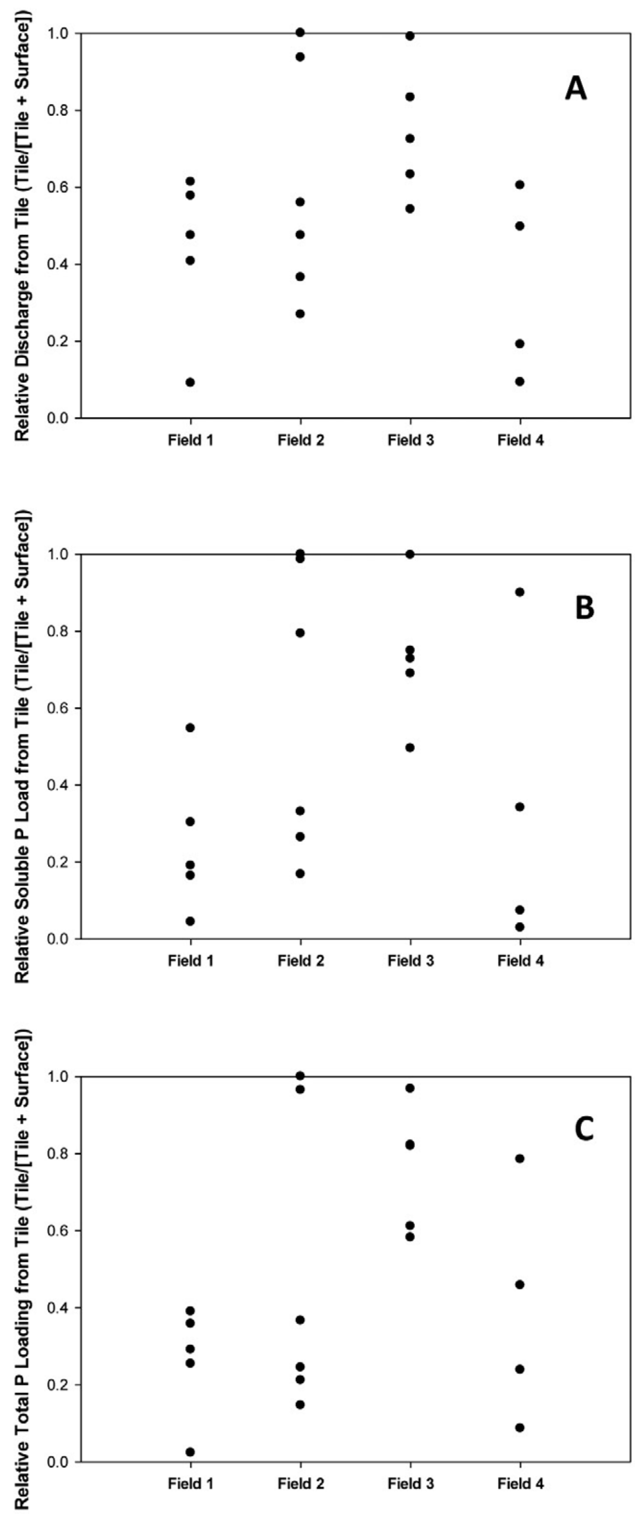

Fig. 4. Relative (A) discharge, (B) soluble P loading, and (C) total P loading from tile relative to the total surface runoff and tile loss by field from the sites monitored in the St. Joseph River Watershed.

Over the sampling period, median SP loads from fields (0.07 kg P ha^{-1}) and tile (0.03 kg P ha^{-1}) together were similar to the median SP loads from the Maumee River (0.13 kg P ha^{-1}). However, for TP, median loads were substantially lower in the Maumee River (0.52 kg P ha^{-1}) compared with the sum of surface runoff TP (0.55 kg P ha^{-1}) and tile (0.34 kg P ha^{-1}) loads. It was not uncommon for the seasonal SP or TP loading

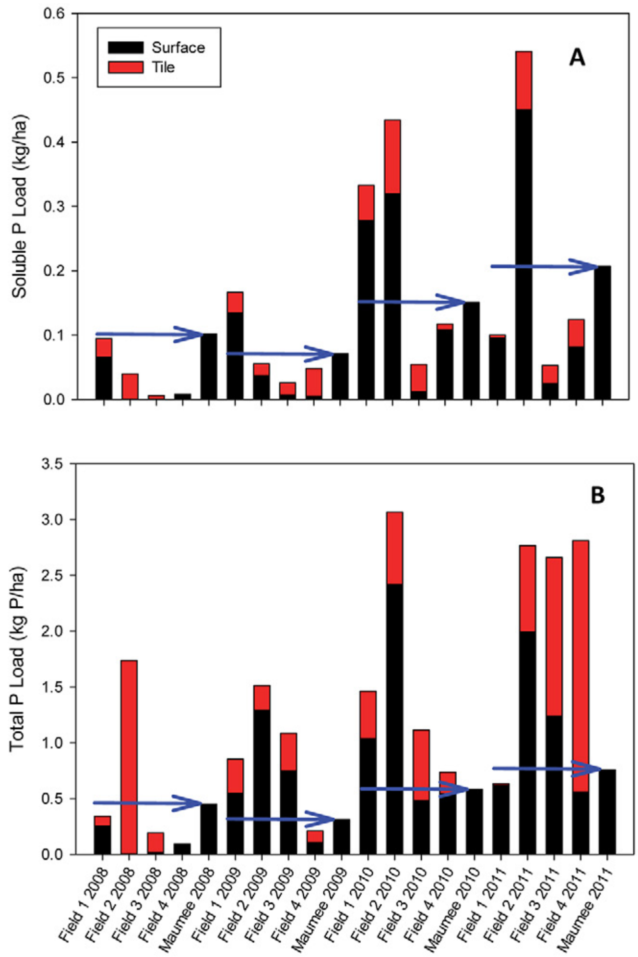

Fig. 5. (A) Soluble P loads and (B) total P loads from four fields in the St. Joseph River watershed and from the outlet of the Maumee River watershed. Data represent the 1 April through 15 November sampling season. The black portion of bars from fields represents surface runoff loading, and the red portion represents the tile loading. Blue arrows point to the corresponding Maumee loading for the period represented by the field data.

from solely surface runoff or tile discharge to exceed the per-hectare loading from the entire Maumee River. There are several potential explanations for this. First, these data may suggest that there is potential deposition of P in the landscape between the fields and the outlet of the Maumee River, which supports the concept of legacy P remaining for some period between initial loss from fields and exiting the watershed (Meals et al., 2010). Another explanation is that the larger watercourses likely intersect groundwater, which is a major component of baseflow. A third plausible explanation is that a substantial portion of land in the watershed has lower P loading than the monitored fields.

Although studies reporting tile P loadings are somewhat rare, our results are very similar to other studies in the agricultural midwestern United States. Plot-scale research of tile discharge in Indiana from tilled plots cropped to corn reported a range of 0.01 to 0.11 kg SP ha^{-1} losses (Kladivko et al., 1991). In a study of three subsurface tiles in Illinois agricultural fields, ranges of 0.05 to 1.0 kg P ha^{-1} for SP loading and 0.2 to 1.3 kg P ha^{-1} for TP loading were observed (Gentry et al., 2007). This study did not have analogous surface runoff discharge monitoring from fields. Algoazany et al. (2007) reported on surface runoff and tile P loads from Illinois and found median SP loads of 0.10 kg P ha^{-1} in tile and 0.07 kg P ha^{-1} from surface runoff. Thoma et al. (2005) reported SP loading from surface runoff in closed depressions ranging from 0.0 to 0.3 kg P ha^{-1} and TP loading in surface runoff discharge ranging from 0.1 to 4.1 kg P ha^{-1}. Although they did monitor tile discharge from these plots, P was not measured in water quality samples. Another study of closed depressions reported SP loading of 0 to 0.06 kg P ha^{-1} and TP loading of 0 to 0.2 kg P ha^{-1} during the growing season from surface runoff (Ginting et al., 2000). This study did not report tile discharge loads. Losses of P through tile are likely a prevalent loss pathway throughout the midwestern United States, particularly where reduced tillage systems may have encouraged the development of macropores. Connectedness of surface runoff to subsurface tile systems is enhanced with the prevalence of macropores, and thus N and P transport may be exacerbated in these systems.

Modeling of agricultural lands in the Lake Erie basin suggest that 1.3 kg SP ha^{-1} and 2.5 kg TP ha^{-1} are conveyed annually to Lake Erie (USDA–NRCS, 2011). The International Joint Commission has set a goal to decrease annual TP loading from the Maumee River basin, the largest single tributary to Lake Erie, by 39% from the 2007–2012 average to 1600 Mg P (IJC, 2013). Similarly, the Ohio Phosphorus Task Force (2013) recommended spring (March through June) loading reductions of 37% from 1275 to 800 Mg P. Given such targets for water quality goals and given that P is transported via surface runoff and tile, conservation practices should be used to reduce P loading from both pathways. Although we have a suite of practices that are known to work for P loading to surface runoff, research is needed to identify conservation practices that will decrease P loading in tile without unintended consequences, such as detrimental yield impacts or increasing loads of other contaminants of concern. As the data presented in Fig. 3 indicate, a direct connection of surface runoff to tile exists through macropore flow, and one goal of practices could be to break this connectivity. Evidence exists that disrupting macropores reduces P concentrations in tile drainage (Simard et al., 2000; Gaynor and Findlay, 1995). Controlling P sources within fields is another class of practices that warrant consideration. For example, the 4R (right source, right rate, right place, right time) nutrient management approach can optimize fertilizer and manure application and minimize the potential for P losses (Bruulsema et al., 2009).

Conclusions

The HNABs in Lake Erie and other fresh water resources are in part due to P loading from agriculture. Tile drainage is necessary to produce crops in much of the midwestern United States; however, tile installation exacerbates nutrient losses from agriculture. Agricultural P loading has generally been considered a surface runoff–dominated process, but our results contradict this conventional wisdom. Between 25 and 80% of the P lost from the fields monitored in the St. Joseph River Watershed was observed to occur from the subsurface tile in these fields. Furthermore, developed macropore flows and tile drainage can connect sources of nutrients in fields directly to a stream channel, bypassing the soil matrix where P could be sequestered, as demonstrated by concomitant peak discharge in surface runoff and tile. These findings suggest that to reduce P loading to reach targets set for Lake Erie, we must not only manage fields to reduce surface runoff P losses but also manage for P transport to tile. Although further research is needed to identify which practices are best suited for such management, the most likely methods are optimizing fertilizer and manure P application and interrupting macropore connectivity between the surface and tile.

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